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WALTHAM ABBEY,

ESSEX, ENGLAND.

Reference: XR 413/9

3rd. November, 1952.

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Attached is copy No.140 of E.R.D.E. Technical Note No. 1/TN/51. Will you kindly acknowledge receipt.

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Because of common interests, circulation has now been extended to include the U.S. J.A.N.A.F. Physical Properties of Propellants Panel. Criticisms and comments will be welcomed.

Yours faithfully,

C. G. Lawson.

for Chief Superintendent,
Explosives Research and
Development Establishment.

Miss E. McAbee,
Plastics Research Section,
Picatinny Arsenal,
Dover,
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MINISTRY OF SUPPLY

EXPLOSIVES RESEARCH AND DEVELOPMENT ESTABLISHMENT.

TECHNICAL NOTE No. 1/TN/51

Consideration of the Mechanical Properties of Rocket Propellants in Relation to their Use in Large Rocket Motors: Part 1. Colloidal Propellants

by

C.G. Lawson.

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CONTENTS

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1. SUMMARY

1.1. The wartime work on cordite is described. A general discussion leads to conclusions as to the measurements which are required to enable the mechanical behaviour of star-centred and other charges to be predicted. The effect of size of charge is considered. Proposals are made for further study of the physical properties of colloidal propellants.

1.2. Further Work.

A similar note is being prepared for plastic and highly-elastic propellants.

2. THE 3-INCH U.P. WORK DURING WORLD WAR II.

During the war a considerable amount of work was done to correlate failures of rockets at their upper temperature limits with the mechanical properties of the propellant. This work was at first concentrated on the 3-inch U.P. with a tubular cordite charge. Hartree (1) examined the general mathematical problems involved and his work was followed up at P.D.E. (2) and extra-murally (3). Later, C.S.A.R. and C.S.,P.D.E. collaborated in more detailed work (4), some of it relating to different charge shapes.

Taking the 3-inch tubular cordite rocket as an example, the peak gas pressure at the head of the charge was 1685 p.s.i., and at the venturi end it was only 1330 p.s.i.(12). The cross-section of the cordite was 5.28 square inches, reduced to 5.13 square inches at the time of peak pressure (0.025 sec.), and the surface area of the supporting grid was 1.8 square inches. The increase in grid pressure due to acceleration of the charge by the grid on projection was 920 lb. wt.. Hence, ignoring friction and considering only forces parallel to the axis, there was an excess hydrostatic pressure at the head end of 355 p.s.i., compared with the grid end. The general hydrostatic pressure at the grid end presumably causes only a negligible bulk strain, without any change in shape, but this excess pressure is equivalent to a direct compressive stress, and is balanced by a force exerted on the base of the cordite charge by the grid.

The total longitudinal compressive stress on the cordite at the venturi end is therefore 179 p.s.i., due to set-back, plus 355 p.s.i., due to gas pressure. Very near the grid, this stress becomes non-uniform over the cordite cross-section, being concentrated to the actual area of contact between grid and cordite; the stress over this grid area is 5.13/1.8 times the average stress, totalling 1520 p.s.i.

Two main types of mechanical failure of the propellant can therefore occur. Firstly, the whole charge is compressed elastically, causing it to barrel out near the grid and restrict the gas conduit. This was the predominant effect for the tubular 3-inch rocket charge, and a satisfactory correlation was worked out between Young's modulus at the upper temperature limit, the stresses involved and ballistic calculations of the deformation required to cause failure.

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Secondly, the approximately threefold stress concentration over the area of contact between the grid and the cordite can, under suitable

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circumstances, cause grid penetration due to plastic flow of cordite. This type of failure occurred with the five-arm cruciform charge, where the first type of failure was largely prevented due to the support given by the metal tube to the propellant. Here again, a fair agreement was obtained between laboratory measurements and practice.

Reasonably accurate predictions could be made of temperature limits with new compositions (F.565/14, F.565/16, F.565/26 etc.) in the 3-inch rocket, based solely on vented vessel measurements of burning rates and laboratory measurements of Young's modulus, hardness etc. (4) (6-11).

3. MODERN TRENDS IN CHARGE DESIGN.

3.1. Almost all present day rockets employ charge designs which eliminate the rapid streaming of hot gases over the metal tube, by using inhibited, internal-conduit, propellant charges. They are often shorter in proportion to their diameter than the wartime fin-stabilised rockets, and are mainly used for boosts or in applications where the acceleration is relatively low. The ratio of gas conduit cross-section to port area is frequently higher than in wartime rockets. The stresses to which the propellant may be subjected are considered below from the points of view of manufacture, storage, rough-usage and firing.

The principal charge shape considered is the star-centred inhibited charge, with the annular space between charge and rocket tube either pressurised by the hot gases, unpressurised (as in the American 'Deacon' rocket) or filled with viscous liquid or a weak jelly or plastic (as in the 7.5 inch boost motor). The multi-conduit charge may involve special problems. Head-end support could be used for a stick-and-tube charge. So far as is known no other charge shapes need individual consideration.

3.2. Manufacture

3.2.1. Extruded Solventless Cordite

The range is being extended to larger and larger diameters, but, apart from the difficulty of using large presses, handling and inspecting large charges, etc., there would seem to be no fresh mechanical problems. The strain at the propellant surface due to expansion at the die is no more (when expressed as a fraction of the perimeter of the extruded charge) than for small sizes, although the linear expansion is larger. Hence the stresses frozen into extruded charges should be no more. The use of complicated charge shapes may give rise to more serious internal stressing, especially if there are lines of stress concentration. From this point of view, the use of a star-section with very pronounced sharp points has proved to be unsatisfactory. In general, the spider supporting any internal pins, etc., in the die should be so mounted that there is a space allowing for consolidation between it and the parallel part of the die. If this is omitted, planes of weakness often occur, corresponding to the spider lines, and the charge is not true to shape. In order to minimise the effect of planes of weakness, it would be desirable to prevent spider lines from coinciding with minimum web thicknesses in the charge.

The presence of internal stressing could be advantageous in certain cases. For example, it might increase the bursting pressure of a thick-walled tube. It is dubious whether advantage could ever be taken of such an effect, due to the tendency of thermoplastics to relieve their stresses on hot storage; in any case, the concomitant disadvantages of expansion at the die and a tendency to revert to a less stressed shape would normally

/predominate.

predominate. Exploitation of the technique whereby the cordite dwells in the die for some minutes should give a product almost free from internal stresses, and of very good dimensional reproducibility. This is being tried by E.R.D.E.

3.2.2. Cast Double Base Propellant

This may have internal stresses on a micro-scale due to its method of manufacture. Cylindrical granules are surrounded by voids of irregular shapes and N.C. concentration-gradients must be produced on casting. The maturing will tend to diminish these concentration gradients, mainly by diffusion of liquid, since it is so much more mobile than entangled N.C. molecules, and the granules will swell bodily to fill the entire space. In other words, the original short cylinders will have been distorted into very irregular swollen shapes. Unless either true solution or plastic flow accounts completely for the change of shape, there will be residual elastic stresses. The extent of this lack of equilibrium, taking the form of large residual concentration gradients plus elastic stresses in severe cases, and negligible concentration gradients plus mild elastic stresses in the case of a good casting, will clearly depend on the nature of the components and the completeness of curing.

There may, in addition, be larger-scale frozen stresses. For example, a difference in rate of gelatinisation of inhibiting material and propellant granules, combined with the restraint of the corset, could give rise to a pseudo-equilibrium in which the inhibiting layer is in tensile stress. On the other hand, shrinkage during casting could give a reverse stress in the inhibitor, and could lead to rupture in the bond or in the propellant.

Summarising, the optimum conditions have to be chosen for each cast propellant system, and the products checked for serviceability. It will be interesting, nevertheless, to try to correlate the ease of plastic flow of swollen granules with temperature and time of curing, to assess the extent to which practical propellants fall short of true equilibrium, and to examine the effects of frozen stresses on molecular orientation, rupture by gas evolution, elongation at breaking point, etc.

3.3. Storage

3.3.1. Normal Storage

Storage at temperatures below 80°F. has little maturing effect on solventless propellants. Changes, presumably in amorphous-crystalline N.C. ratio, are slow. For example, cordite after processing or reheating has an abnormally low Young's modulus, and it takes days around 80°F., or weeks around 60°F., for the normal value to be re-established.(14)

Very interesting delayed elastic strains and 'pseudo-plastic' deformations occur under moderate storage stresses, for example, the sagging of a large stick of cordite supported horizontally at its ends. A few hours hot storage in the absence of stress usually restores the original shape, if it does not, in fact, 'unfreeze' some even earlier history of the specimen, previously frozen into it as an internal stress at a higher temperature. All this can be stated in terms of a Maxwell spring-and-dashpot model system, with an extremely large number of elements covering a range of relaxation times of many million-fold, provided there is a very large temperature coefficient of each relaxation time and a non-Newtonian liquid in the dashpots. Thus the displacement of an element which corresponds virtually to a plastic flow at low temperatures is only a delayed elastic flow at a higher temperature. It is a matter of future work to correlate the temperature coefficients at one end of the spectrum of relaxation times with those

/at the

at the other, and to see the effect of changes in molecular weight of N.C., etc..

3.3.2. Cold Storage

This also has no effect on cordite, but there is one unconfirmed case where S.C. cordite became brittle after being kept for a winter at around 6-8^{o}C. Subsequent heating for one hour at 50^{o}C. removed the effect. Several thousand specimens were studied in an unsuccessful effort to repeat this work(15)

3.3.3. Hot Storage

On hot storage, there is a moderate increase in Young's modulus during the first fortnight, after which it is constant for a long time until chemical degradation supervenes. Any stresses frozen in the charge tend to become relaxed (16), and often a charge will bend or distort when heated, especially if it was stressed during cooling after extrusion. There is a need for more quantitative knowledge of such effects.

3.3.4. Temperature Cycling

Temperature cycling giving thermal gradients, can induce stresses due to differential thermal expansion and contraction. There is scope for measurement of 'elongation at break' of various compositions, especially at low temperatures, so that this (combined with a knowledge of thermal expansion, specific heat, thermal conductivity, modules of rigidity and bulk modulus at various temperatures) can be used to predict the maximum rate of change of temperature to which a charge can be subjected without rupture. This rate will presumably be much less at low temperatures than at normal temperatures, and less on cooling than on heating.

Stresses due to differential thermal expansion, as well as to plasticiser interchange, are also likely to arise with inhibited charges. The coatings employed have been chosen to have properties very similar to those of propellants, but small differences are inevitable. Such differences have not been fully studied.

There is a clear requirement for an inhibiting material which can deform much more easily than the propellant, and without rupture or adhesive failure throughout such temperature changes. Such deformation could, in principle, be either plastic or elastic. This will be considered in E.R.D.E. Technical Note No. 3/TN/51 (in preparation).

3.3.5. Rocket Motors

The foregoing is effectively concerned with the storage of isolated colloidal propellant charges. In the case of made-up rockets, the supports of the charge constrain it more or less rigidly in a symmetrical position in the rocket tube, and hence impose stresses on it. This constraint is of two sorts, firstly, reaction against the weight of the charge, normally negligible, and secondly, self-stressing between charge and supports due, in general, to differential thermal expansion, and operative only at high temperatures. The extent of this self-stressing is a function of individual charge dimensioning and design, but laboratory investigations will be required to furnish the data required for calculating it, including measurements of coefficients of expansion of propellant and inhibitor, moduli of rigidity and the degrees of strain at which rupture or 'cold flow' occurs, all over a range of temperature around the upper temperature limit

/of the

of the rocket. At some temperature near the upper limit, the charge will become a tight fit in the tube. At temperatures above this it will first be strained elastically and then undergo plastic flow (so-called 'cold-flow'), It may turn out to be possible to rely on a definite degree of elastic strain before any irreversible cold flow or excessive stresses on the metal rocket tube occur; if so, the motor will be correspondingly more efficient. Such a condition at high temperatures would give support against firing set-back and might enable a 'softer' propellant to be used than was otherwise the case, but it would entail a precision moulding of charge plus inhibition, and close tube tolerances. It might be possible for the charge to be 'self-moulding' by deliberately making it a tight fit in the tube so that it flowed, in any case, to some extent on its first heating, enabling wider tolerances to be used.

3.4. Rough Usage

The trend in rocket tube design is such that with highly-efficient large motors the colloidal propellant charge is likely to be at least as strong as the tube. A fall of a motor six feet on to concrete would probably be equivalent to some twenty feet drop of the empty lightweight tube, as regards stresses in the tube itself. There is everything to be said for low modulus elastic supports of the propellant within the tube for these supports to bear on as large an area of the propellant as possible and for the propellant in the vicinity of such supports to be as free as possible from regions of potential stress-concentration. These are really all matters for the charge designer. The best the propellant research and development groups can do is to devise compositions as strong as possible. Wartime work indicated little hope here (4) and the only important long-term prospect would be to include polymers other than N.C. in the propellant. New plasticisers for N.C. will be kept under review but no startling advance can be expected, either in improving impact strength without impairing other properties or in lowering the temperatures at which propellants become very brittle.

3.5. Firing

The principal sources of stress on firing are set-back and unbalanced gas pressures, transient (due to ignition or secondary peaks) or persistent (due to absence of pressurisation around the charge). Exact stress analysis is a function of individual charge design and cannot be attempted here. General principles can, however, be considered for the various types of charge. So far as is known, all colloidal propellants can withstand any degree of uniform hydrostatic pressure (unless they contain fissures), so that only unbalanced stresses are considered.

The forces due to inertia on set-back are equal to the mass supported times the acceleration. Therefore these forces are at a maximum at the points of support. Since the tendency of thermoplastics to fail (by rupture or plastic flow) is roughly an exponential function of stress, only these maximum stresses need be considered. Clearly, the support should be spread over as big an area of the surface as possible. The worst cases will be head-end support of a central propellant stick charge and 'grid' support of a tubular (or cruciform) charge. Each involves a mean stress equal to the mass of the charge times its acceleration, divided by the actual part of the area of the cross-section upon which the support is concentrated.

The mass is equal to density time length times average cross-section, and the acceleration is equal to the specific impulse divided by the time of burning and to the ratio of all-up weight to propellant weight.

$acc = \frac{I_{sp}}{t_b} \times \frac{\text{mass of propellant}}{\text{total mass}}$

/If the

If the support at the start of burning covers a constant proportion of the cross-section, say about one third, as in the wartime 3-inch rocket, the actual diameter of motor does not directly affect the charge-supporting stress, which will clearly be highest at the start of burning. In this event a given motor can be scaled-up linearly in all respects, provided the acceleration is made inversely proportional to the length. This would be the case for a given charge shape and propellant composition because the web thickness (and hence the time of burning) is proportional to the length.

However, the general trend of guided missile development requires a uniform acceleration during the boost period as large as the control mechanism (electronic equipment, etc.) can stand, so as to minimise the time required for the missile to reach the target. The tendency with larger boost motors is, therefore, to use faster-burning propellants, and, if necessary, multi-conduit charge designs to minimise web thickness. The acceleration is likely to be up to 50 g at the upper temperature limit. For this constant acceleration, the stress acting on the propellant will be proportional to the length of the motor, both for boost and sustainer motors.

There is, however, a stress-concentration at the edges of the support. In the case of a grid, wartime work proved that 'grid indentation' was minimised by rounding-off its edges. In certain other trials, an increase in grid support area appeared to be counteracted due to the edges of the grid coming near to the boundary of the charge, where lack of lateral support caused the propellant to fail. It is suggested that rocket designers use photoelastic models or other methods of non-destructive testing to indicate stress-concentration, so as to develop the best designs of support to the charge.

Unbalanced transient gas pressures have often been cited as a cause of failure of rockets, and met by drilling tubular charges, using Boys' rods, and carefully choosing the disposition of ignition charges. There is very scanty information about the behaviour of colloidal propellants under rapidly imposed stresses of this sort. Even in the case of sustained pressure differences (as in the American 'Deacon' rocket), data for 'elongation at break' of samples broken in times of two seconds and less are practically non-existent in this country.

The elongations imposed in a charge which is not supported externally can be considerable. Assuming that the propellant is incompressible, a one per cent. increase in external diameter is equivalent to an average elongation at the surface of the conduit of four per cent. if the cross-section of the actual propellant is 75 per cent. of the gross cross-section of the charge, or six per cent. for a 'loading density' of 83 per cent. The elongation at the points of the stars might well be two or three times this average figure. It is therefore necessary that the propellant should be capable of an elongation at break of some ten to twenty times the change in diameter.

Similarly, if the charge is supported by the rocket tube, and the latter stretches by a half per cent. on firing, parts of the propellant may be stretched five per cent. or more.

4. PROPOSALS FOR FURTHER WORK

4.1. Factors Related to Motor Design

The data quoted for the wartime 3-inch rocket were only obtained after extensive calculations and firing trials. Similar figures are not yet available for many newer motor designs, nor can the foregoing general

/considerations

considerations be crystallised without them. For example the calculation of the stress on the propellant charge due to gas pressure differences at the ends, requires a knowledge of venturi and gas-conduit sizes, the rate of burning and erosive burning characteristics of the propellant (particularly at the upper temperature limit of usage) and the stress-concentration of the support. In the case of at least one urgently required boost motor, large-scale manufacture of the new propellant composition is not started, and measurements of its restriction ratio have not yet been made. In order to expedite the work required to solve such difficulties, propellant and ballistics working parties have recently been set up between C.S./.E.R.D.E. and C.S./R.A.E./R.P.D. for study of guided weapons, and also with C.E.A.D. for unguided rockets. It has been agreed that E.R.D.E. will study the stress-concentration in models of sections of propellant charges, by a photoelastic technique.

4.2. The Mechanical Properties of Propellants

4.2.1. The wartime work shewed that routine measurements of Young's modulus, tensile strength, impact strength and hardness were very valuable. These measurements, usually made at two or three temperatures on all important new compositions, were restarted in 1949. It is the main purpose of this note to review what forther work on propellant rheology should be undertaken, consistent with the limited resources available.

4.2.2. Manufacture

There is a general requirement for easy manufacture, coupled with a product as 'hard' as possible. This was realised some years ago, and a rolling mill has now been completed which measures the pressure between the rolls and the driving torque as a function of temperature, speed of rotation and reduction in thickness. By these means it should be possible to give the factories valuable design data, and also to select more precisely the best compositions for use. A tensometer with extrusion cylinder attachment (13) is awaited, and a modified Scott-Piper plastometer has been made. It is hoped with these instruments to obtain a correlation between absolute measurements of plasticity at various rates of shear, and processing stresses. Plant experiments with dies of various designs, etc., are also in hand, but previous experience has shewn the results of such work to be disappointing, due to the difficulty of temperature control etc. Eley (16) investigated during the war, the plastic flow of cordite but further work, particularly on compositions harder than S.C. cordite, is required and it is proposed that the main research effort be put on this work during the next year.

The homogeneity of cast double base charges is studied by etching, by inference from the results of measurements on samples large in comparison with the original granules of casting powder, and by interrupted burning.

Other proposals have been to use a Schlieren technique to explore variations in refractive index, to develop a partial solution method of chemical analysis or to make use of a micro-hardness tester (as used on jewels and microscopic pieces of metal), but it is proposed to defer such work.

4.2.3. Storage etc.

The measurements required to clarify certain storage problems discussed in this note are mainly in the field of 'cold flow', and associated delayed-elastic effects. A simple apparatus for compressing small pellets of propellant is now available, and a more elaborate machine is being made.

/It is

It is planned to start this work very soon.

The rupture of propellants due to thermal gradients is not considered to be an urgent problem, and measurements of elongation at break at low temperatures with a slow rate of loading will be deferred.

4.2.4. Usage

Most problems are covered by existing routine tests, but work using rapid rates of loading is required. Fortunately, urgent problems involving these properties are perhaps best studied by direct tests on sections of rocket charges. It is proposed, however, to obtain equipment for measuring Young's modulus by the vibrating strip method, and to design apparatus for measuring hardness, tensile strength and elongation at break for rapid loading. This work will follow that on plasticity.

4.2.5. Summarising, the following measurements on colloidal propellants are desirable (in order of urgency):

(i) Routine tests of Young's modulus, tensile strength, impact strength and 'hardness' on all important new compositions, at three temperatures, as already carried out;

(ii) Plastic flow at high stresses, simulating manufacturing processes, and at lower stresses, simulating storage under adverse conditions. Further investigation of delayed elastic deformation under similar conditions. In general this work would be confined to temperatures between 40°C. and 80°C;

(iii) Study of photoelastic models for analysis of stress distribution under complicated loading conditions;

(iv) Tensile tests under rapidly applied loads, with accurate measurements of elongation at break (at all temperatures);

(v) Tensile tests at low temperatures, with accurate measurements of elongation at break (using slowly applied stresses);

(vi) Investigation of residual internal stresses and inhomogeneities particularly in cast double-base propellants, and their effect on failure by internal gas evolution etc.

The above work should first of all be carried out on existing service and experimental propellants, but extension to cover compositions containing N.C. of low viscosity, 'non-cracking' compositions, etc., would have to follow.

Standard inhibiting materials should be included.

/Bibliography

5. BIBLIOGRAPHY

1. D.R. Hartree, P.D.E., 1941, "Investigations of the Internal Ballistics of U.P.'s."

2. P.D.E. Report 1942/49.

3. R.P. Fraser, U293/41, "Report on Deformation of 3-inch T.P. Cordite under Pressure."

4. A considerable body of reports by A.G. Ward and co-workers published by A.R.D., 1943-45 (see 5-11), (14), (17). Some give cross-references to P.D.E. reports covering firing trials etc. See also A.R.D. Report 8/47 by K.D. Errington.

5. A.R.D. Explosives Report 655/44 (5-arm cruciform charge).

6. A.R.D. Explosives Report 236/45.

7. A.R.D. Explosives Report 255/45.

8. A.R.D. Explosives Report 203/45.

9. A.R.D. Explosives Report 254/45.

10. A.R.D. Explosives Report 264/45, 580/44.

11. A.R.D. Explosives Report 176/43.

12. P.D.E. Report 1942/12.

13. Nancarrow, British Rheologists' Club Bulletin, 1949.

14. A.R.D. Explosives Report 209/45, and previous reports.

15. A.R.D. Explosives Report 234/46.

16. D.D. Eley and C.D. Pepper, Trans.Faraday Soc., 1947, 63, 559.